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Long-range spin transport in superconductors

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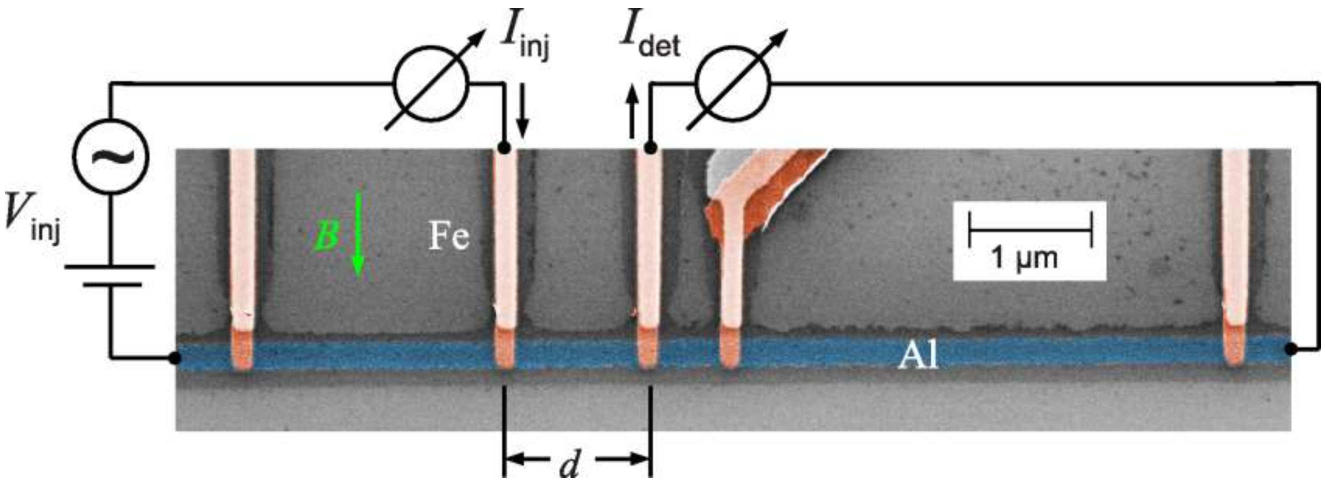
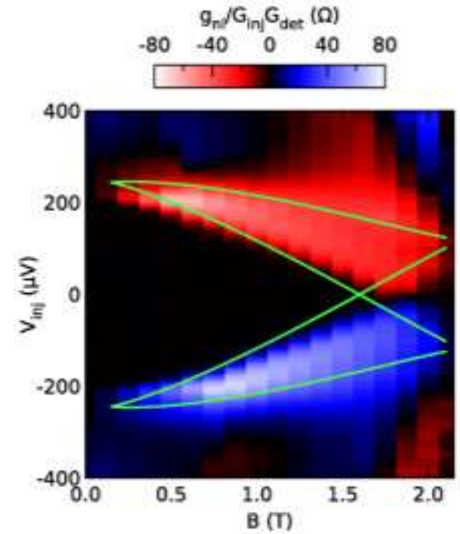
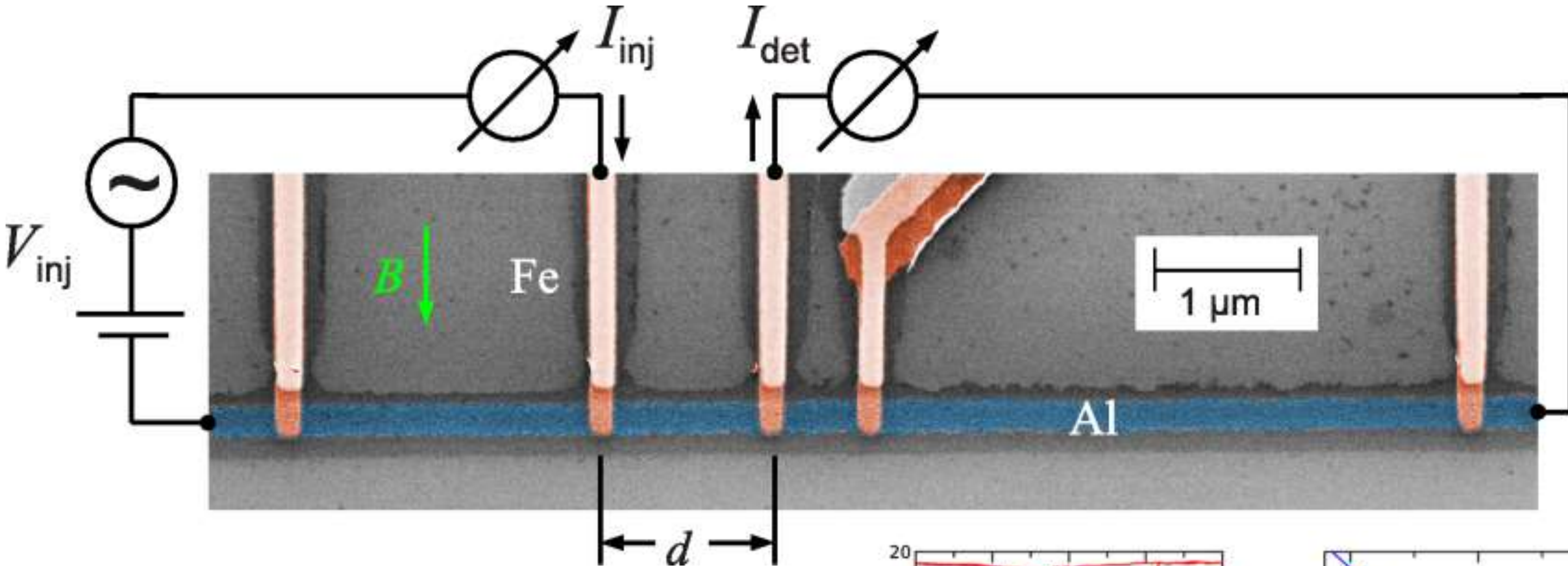
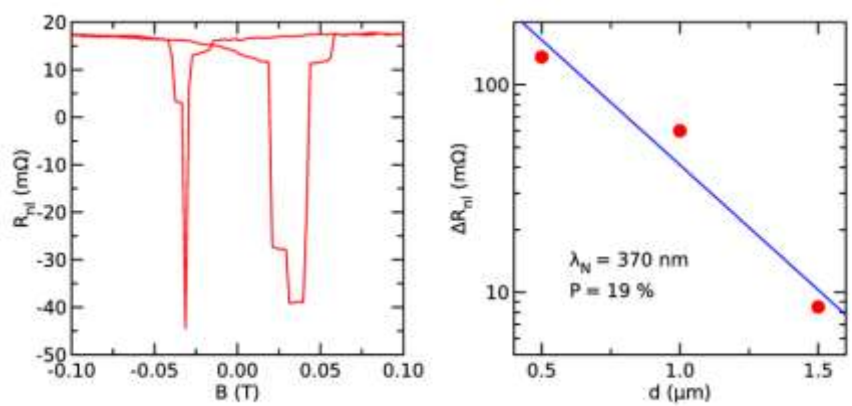




Experiment – *samples*



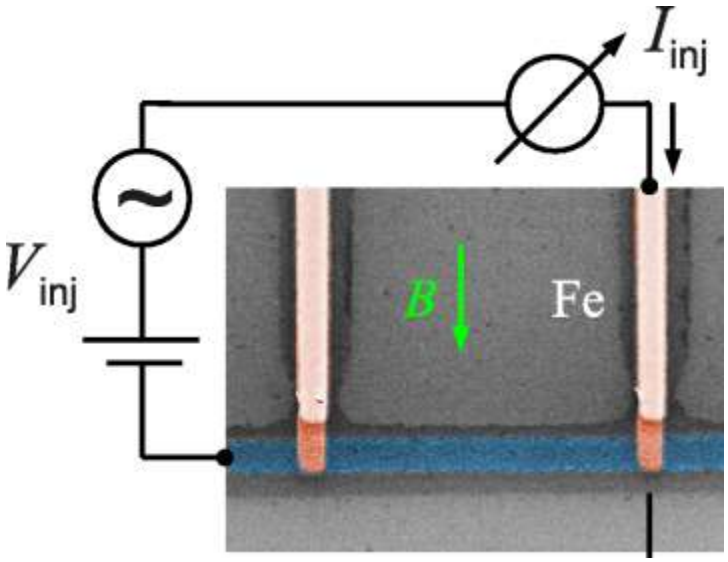


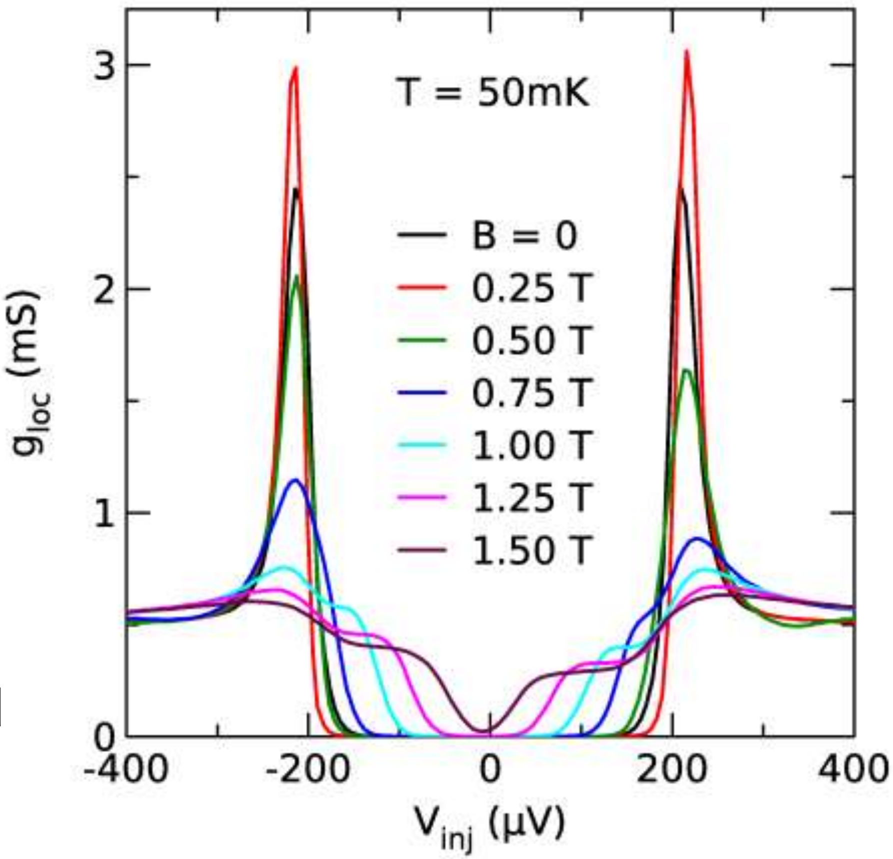
- film thickness ~ 12 nm
- contact distances *d* ~ 0.5 µm – 8 µm
- magnetic field *B* || iron wires
- parallel magnetization alignment

Hübler et al., Phys. Rev. Lett. **109**, 207001 (2012)

normal-state spin-valve:
→ spin diffusion length $\lambda_N = 370$ nm

Experiment – *junction characterization*

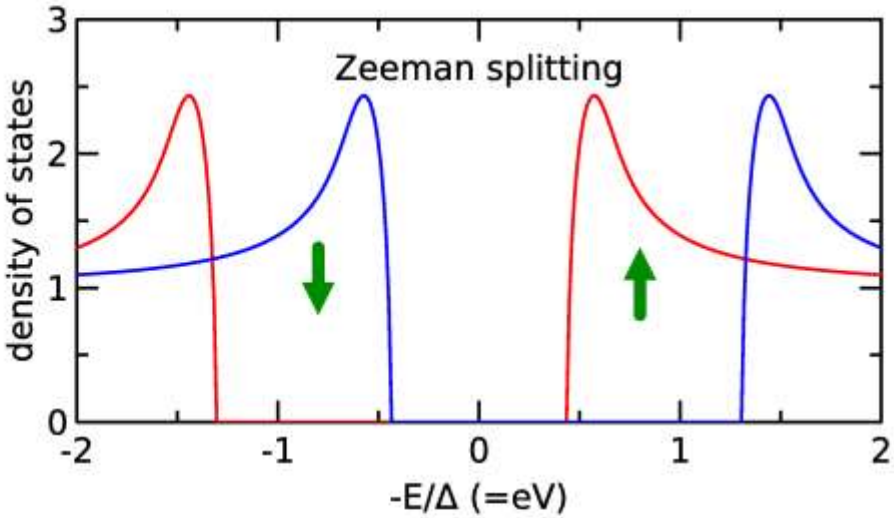




local conductance

Zeeman splitting in the magnetic field

Model – *Zeeman splitting*



Zeeman-splitting of DOS (semiconductor model)

$$n_{\downarrow,\uparrow}(E) = n(E \pm \mu_\mathrm{B} B)$$

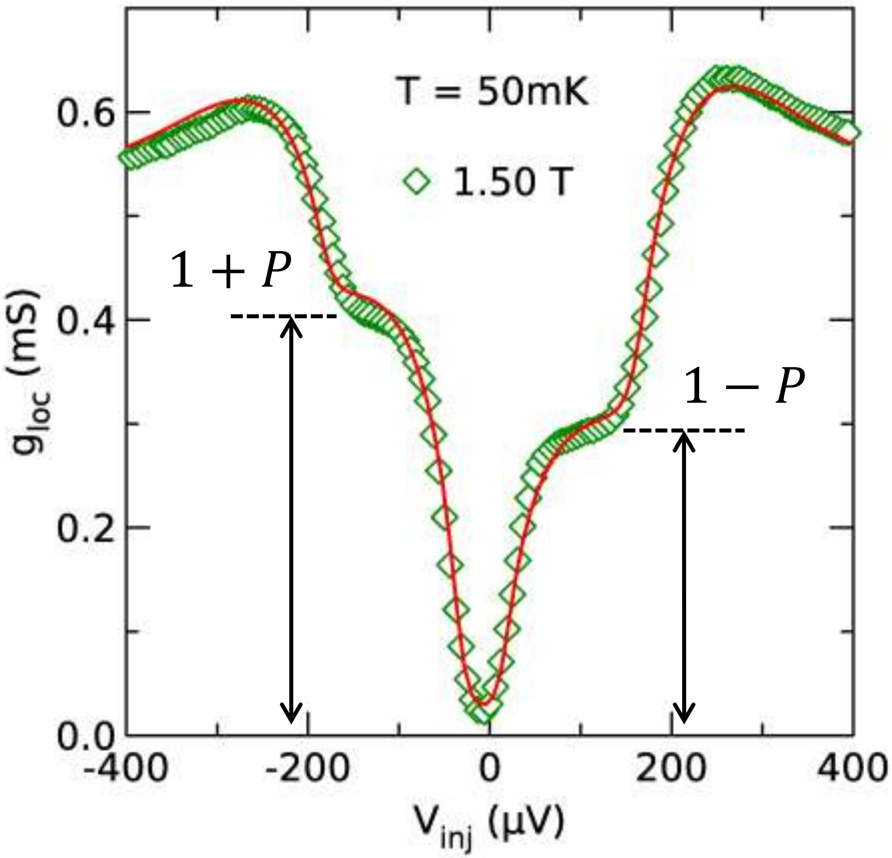
Charge current $I = \frac{1}{e}\int [G_\downarrow n_\downarrow(E) + G_\uparrow n_\uparrow(E)]\{f(E-eV) - f(E)\}dE$

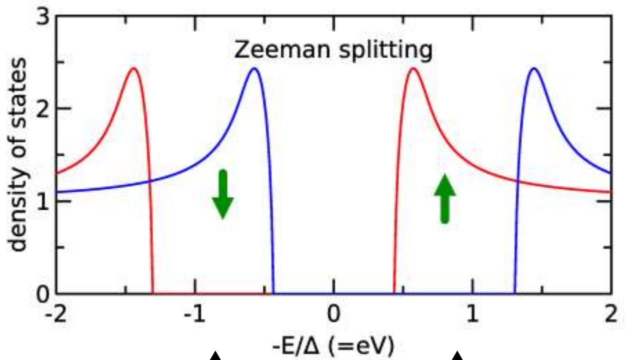
Tedrow & Meservey, PRL **26**, 192 (1971)
Meservey & Tedrow , Phys. Rep. **238**, 173 (1994)

$$G_{\downarrow,\uparrow} = \frac{G_\mathrm{N}}{2}(1 \pm P)$$

Experiment – *junction characterization*

$Al/Al_2O_3/Fe$





superconductor acts as spin filter

asymmetry

$\rightarrow$ determination of $P = \frac{G_\downarrow - G_\uparrow}{G_\downarrow + G_\uparrow}$

$P = 19\ \%$

(consistent with spin-valve experiments)

Experiment – *local vs nonlocal conductance*

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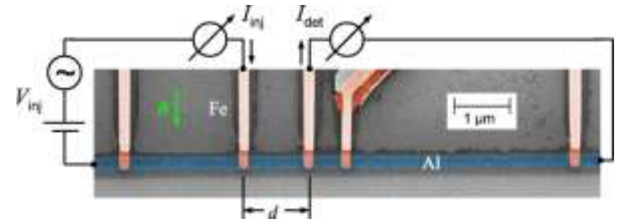
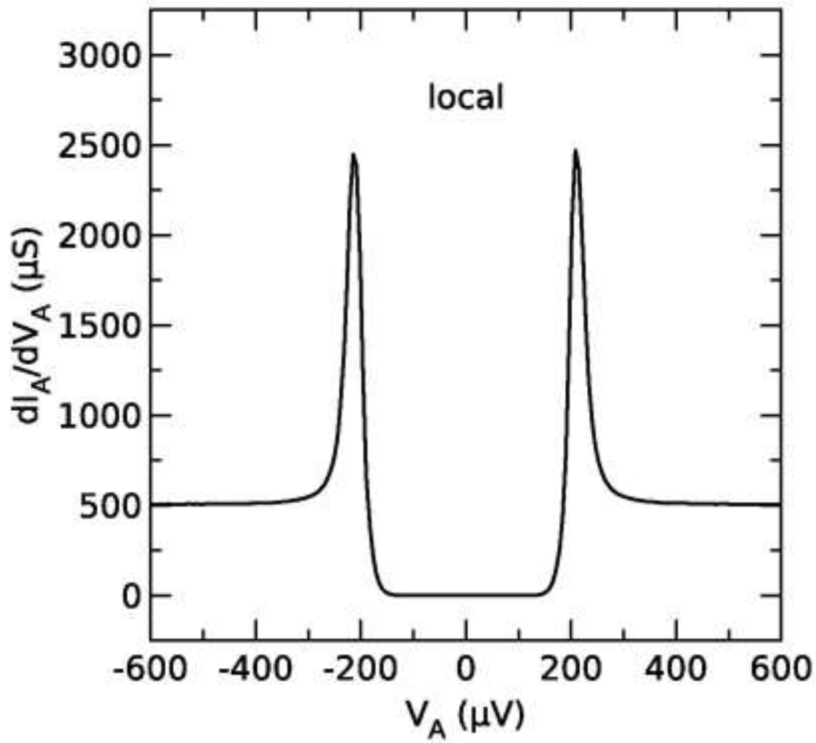
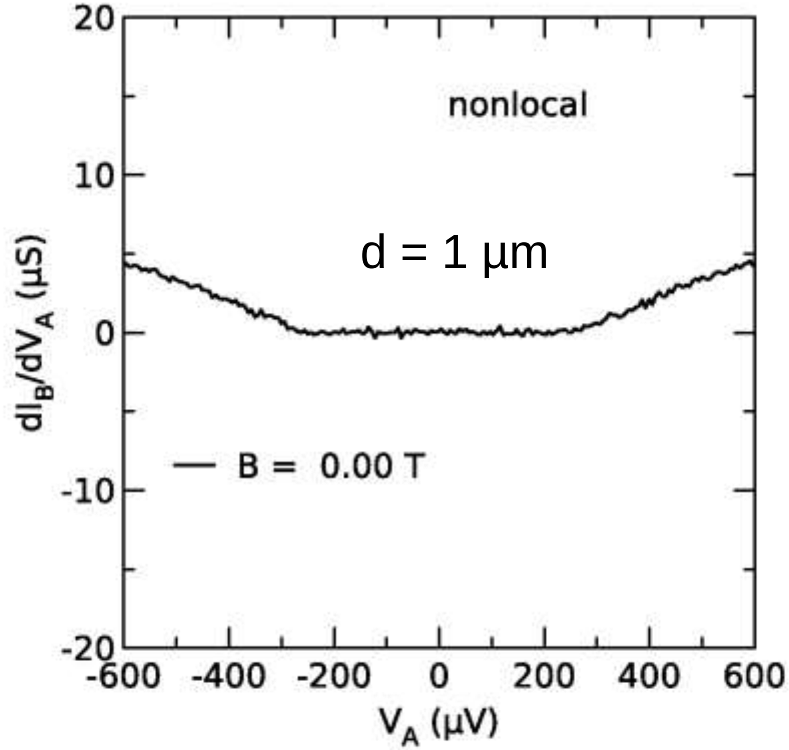
B = 0

$Al/Al_2O_3/Fe$





density of states

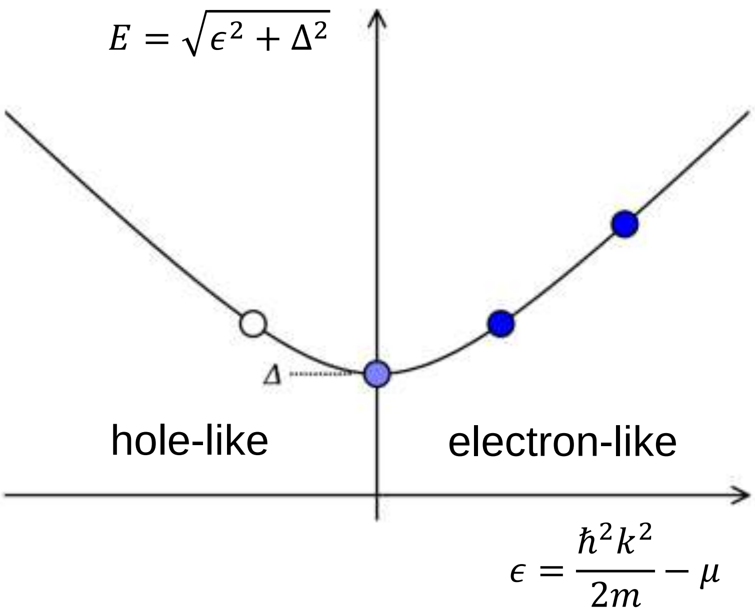


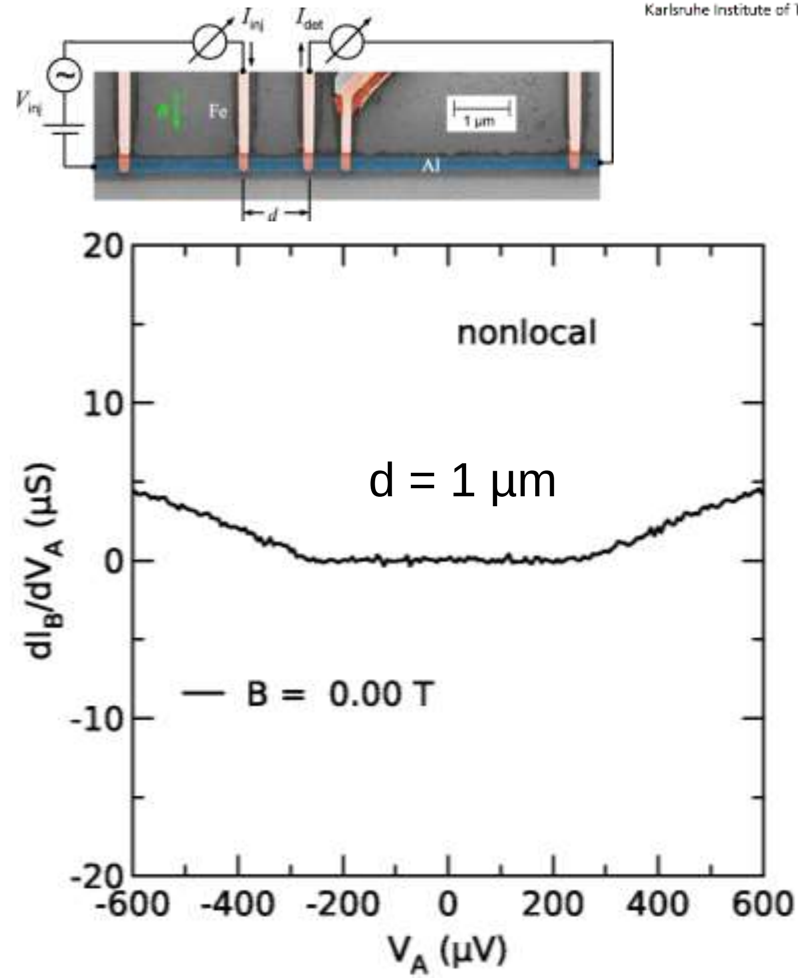
charge imbalance

Clarke, Phys. Rev. Lett. **28**, 1363 (1972)
Tinkham & Clarke, Phys. Rev. Lett. **28**, 1366 (1972)

Experiment – *local vs nonlocal conductance*

quasiparticle dispersion





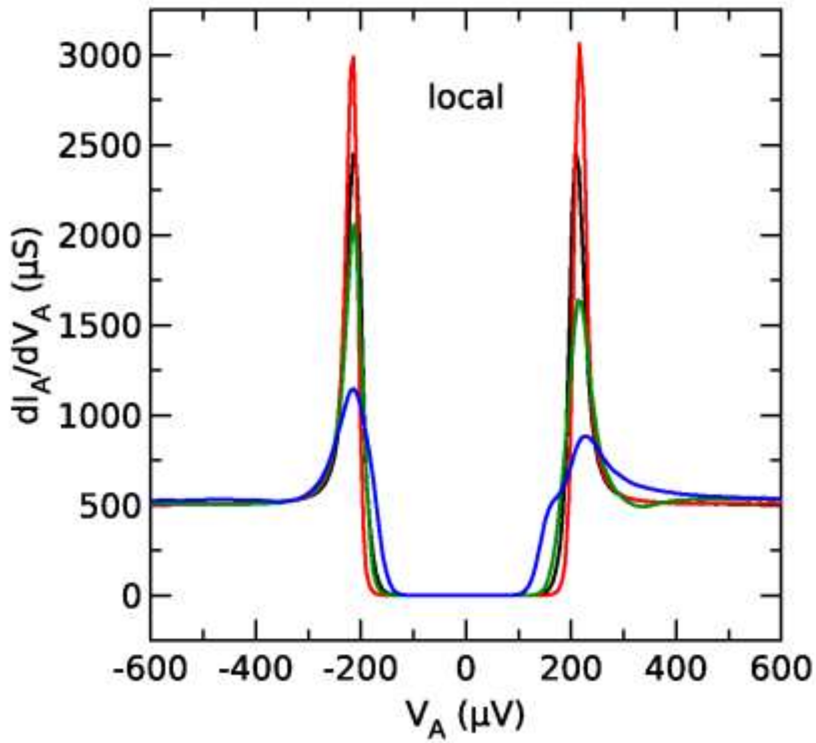
charge imbalance

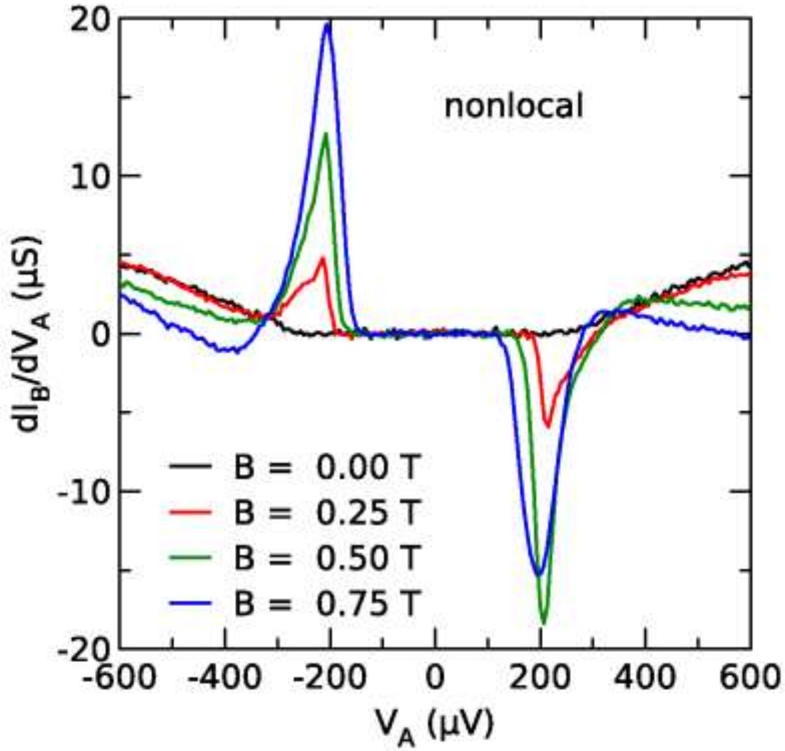
Clarke, Phys. Rev. Lett. **28**, 1363 (1972)
Tinkham & Clarke, Phys. Rev. Lett. **28**, 1366 (1972)

Hübler et al., Phys. Rev. B **81**, 184524 (2010)

Experiment – *local vs nonlocal conductance*

B > 0



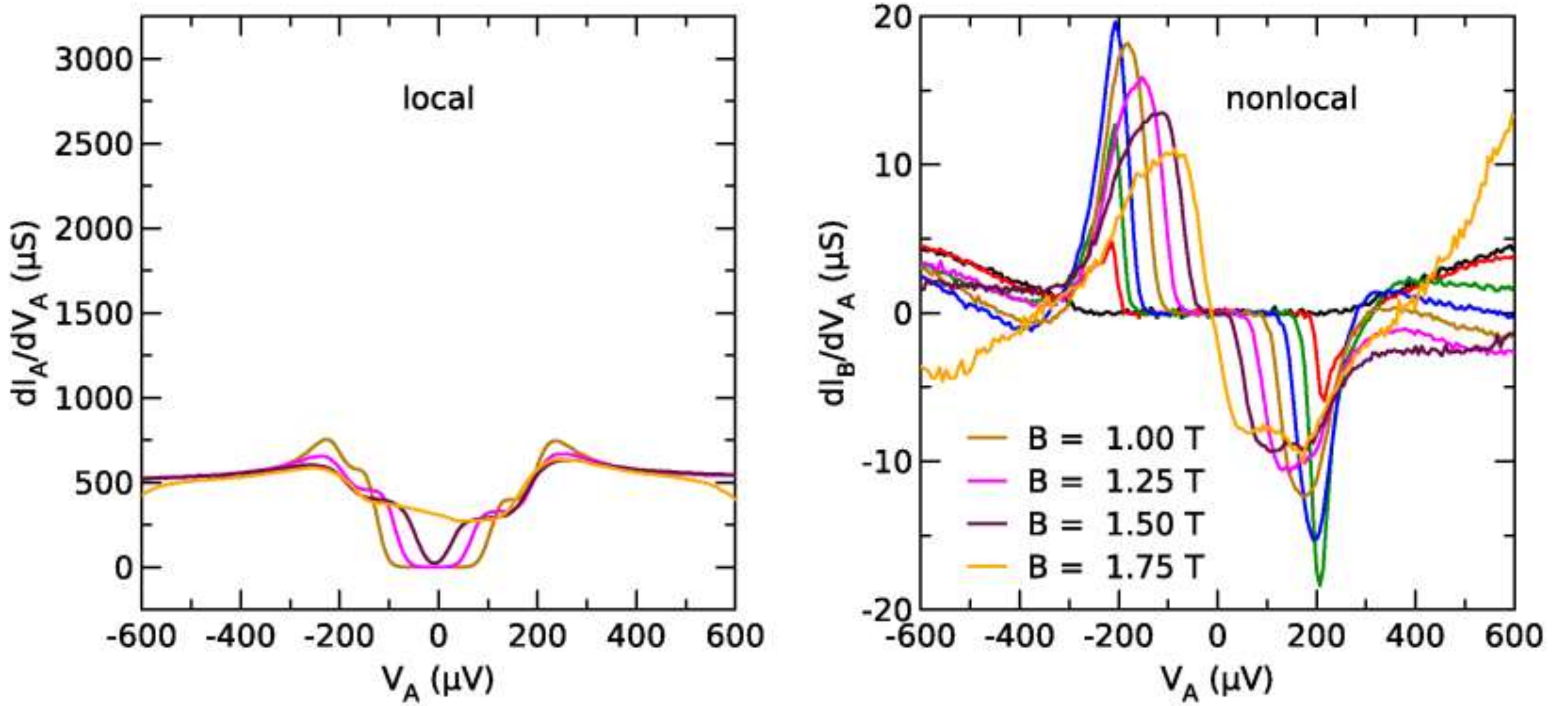


broadening & Zeeman splitting

asymmetric features appear

Experiment – *local vs nonlocal conductance*

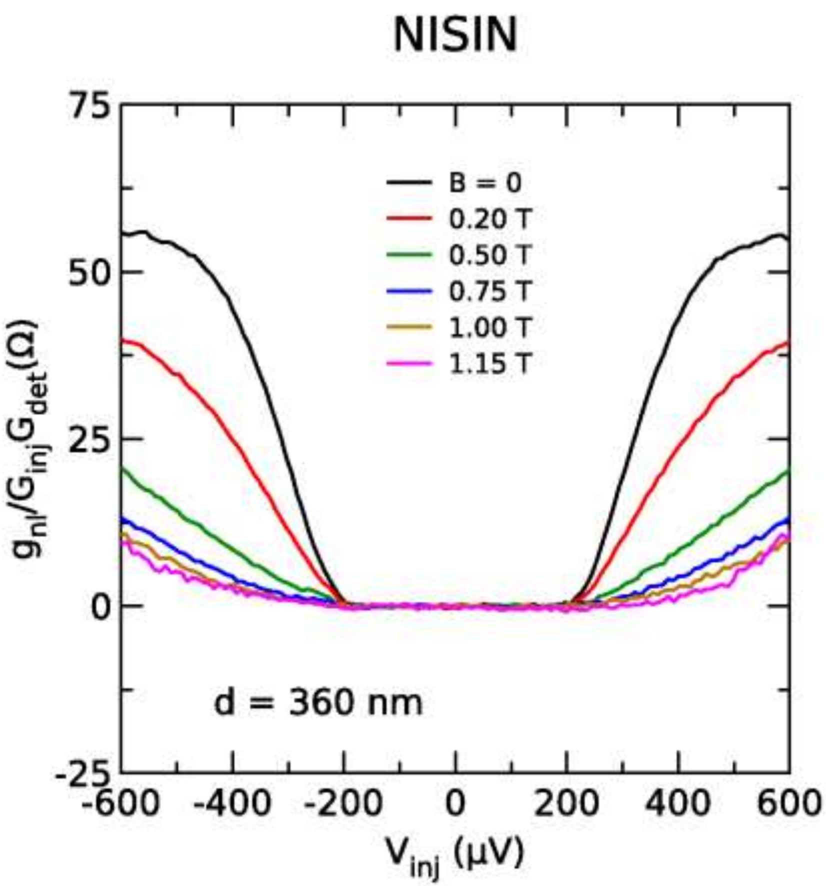
B ≫ 0



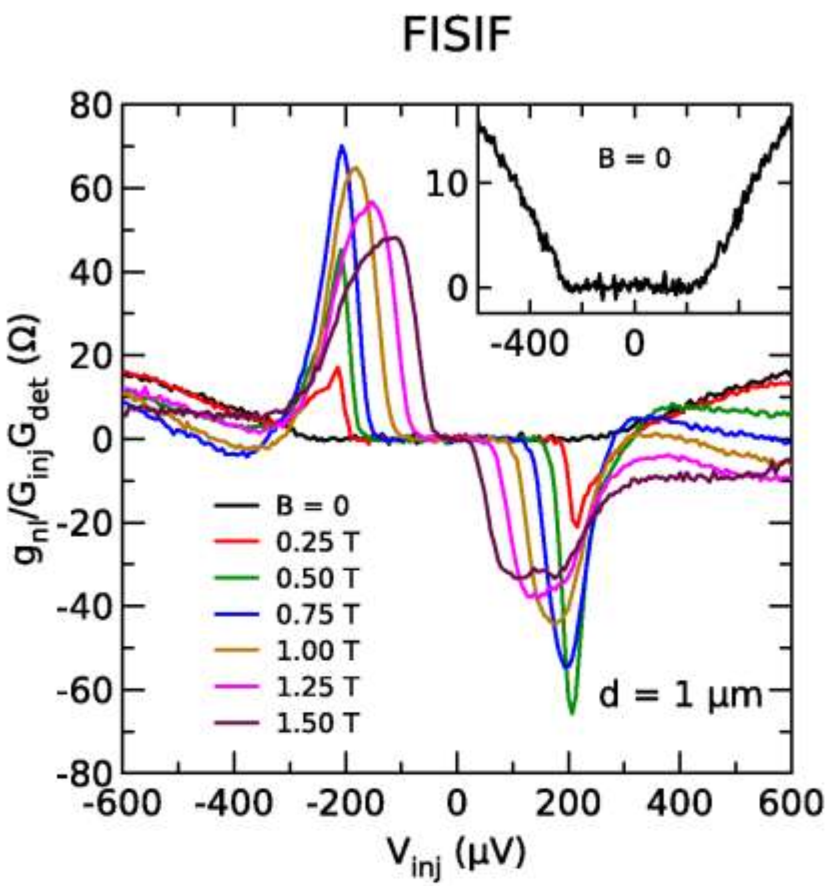
Zeeman splitting grows

features broaden

Experiment – *normal vs ferromagnet*



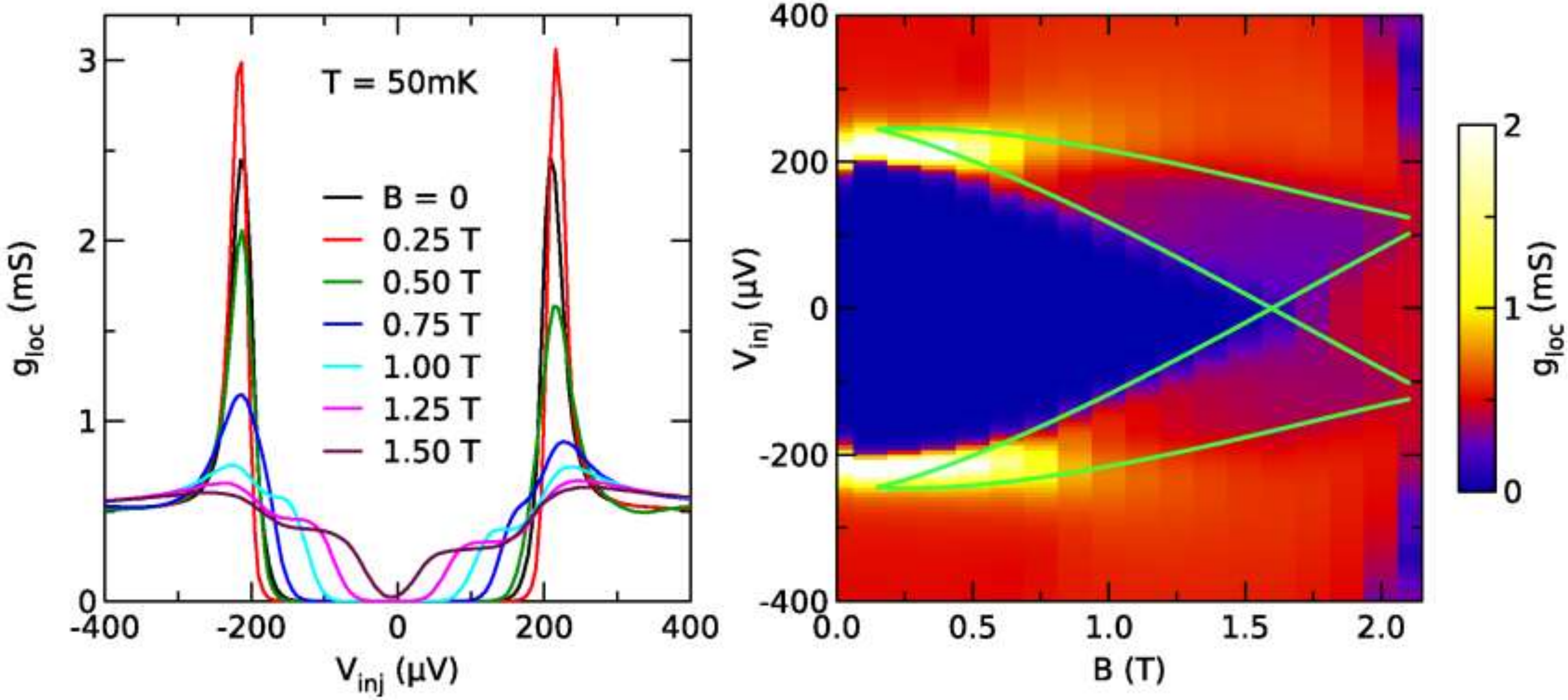
only charge imbalance



charge imbalance + asymmetry

similar results: Quay et al., Nat. Phys. **9**, 84 (2013)

Experiment – *local conductance*

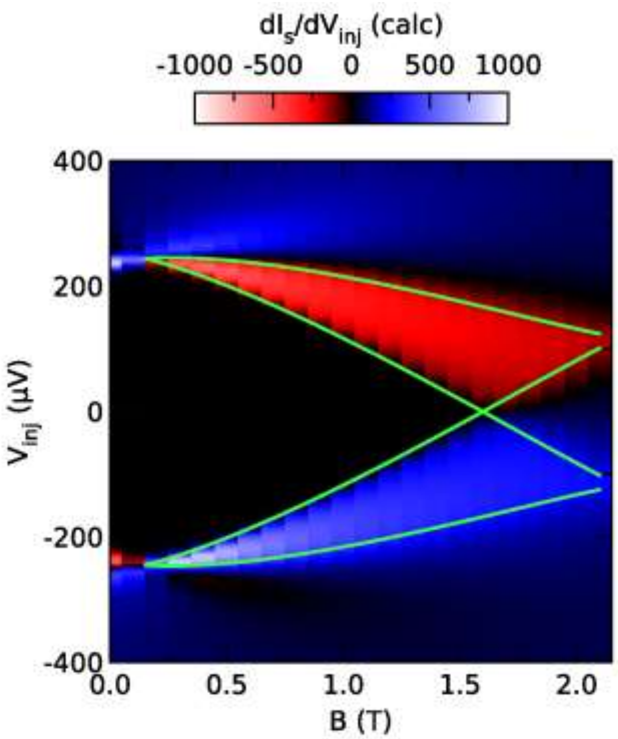


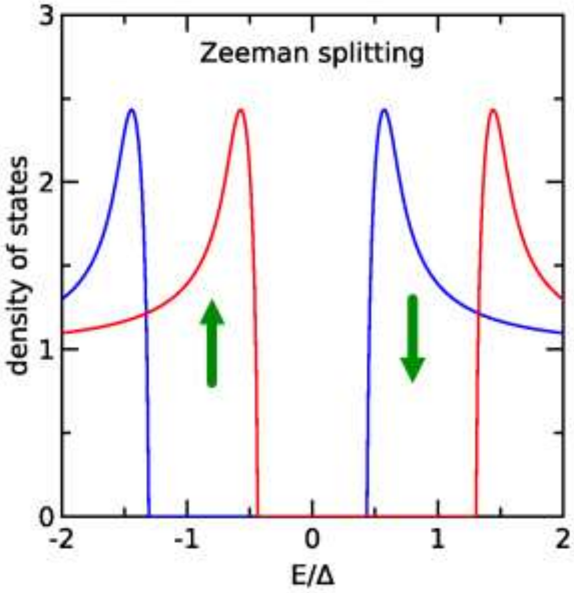
$$I = \frac{1}{e}\int [G_{\downarrow}n_{\downarrow}(E) + G_{\uparrow}n_{\uparrow}(E)]\{f(E - eV) - f(E)\}dE$$

wedge-shaped regions: only one spin band contributes

superconductor acts as spin filter

Experiment – *predicted spin injection*



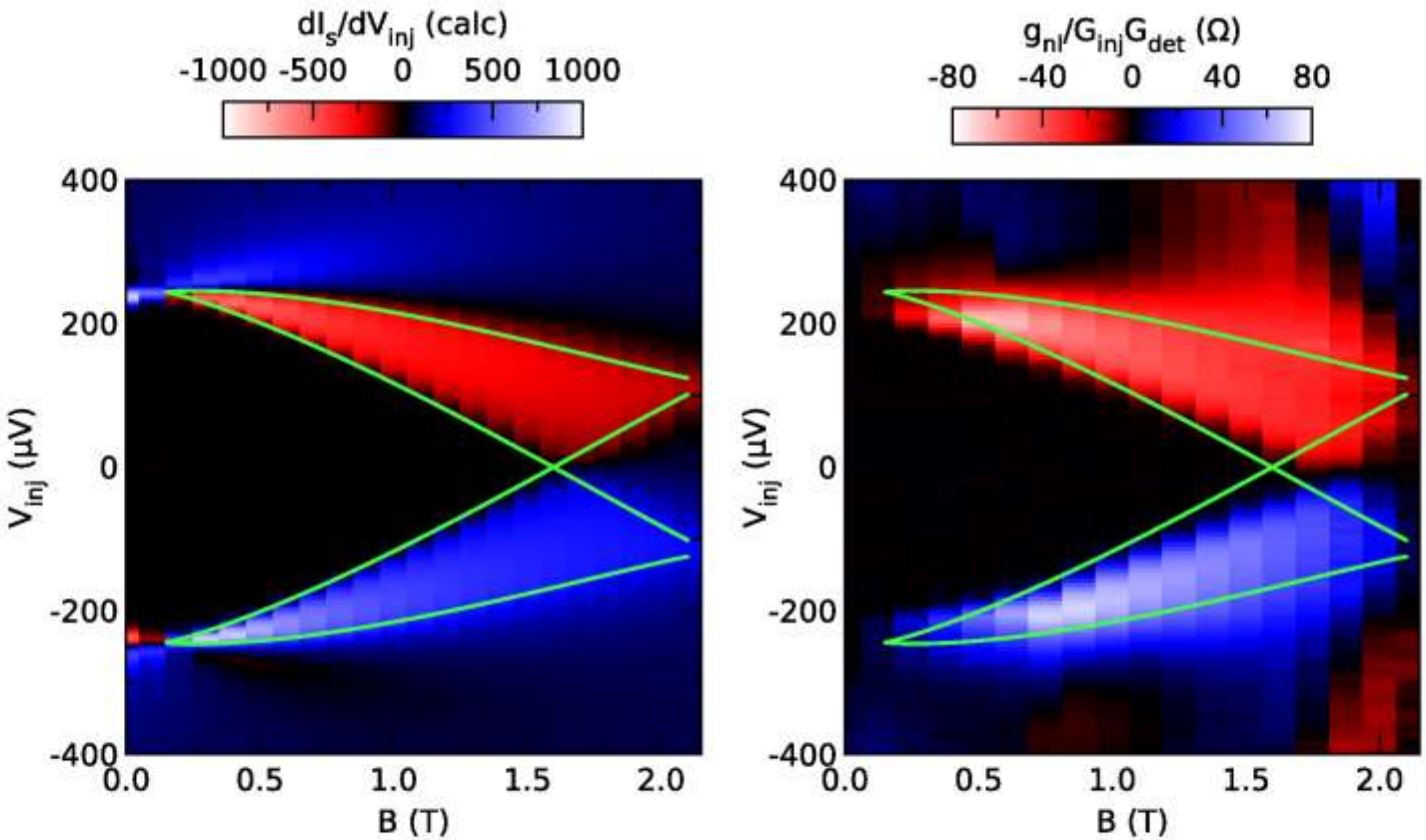


Spin current $I_s = \frac{1}{e}\int [G_\downarrow n_\downarrow(E) - G_\uparrow n_\uparrow(E)]\{f(E-eV) - f(E)\}dE$

$$I_s \propto \frac{G_\downarrow - G_\uparrow}{G_\downarrow + G_\uparrow} + \frac{n_\downarrow - n_\uparrow}{n_\downarrow + n_\uparrow}$$

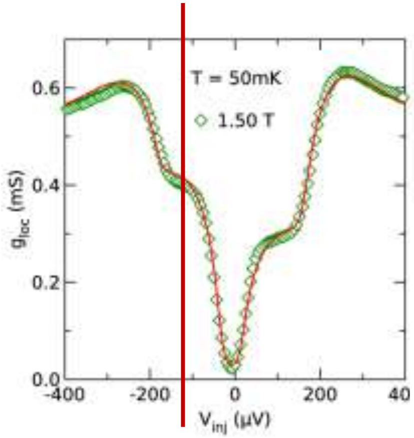
see also Giazotto & Taddei, Phys. Rev. B **77**, 132501 (2008)

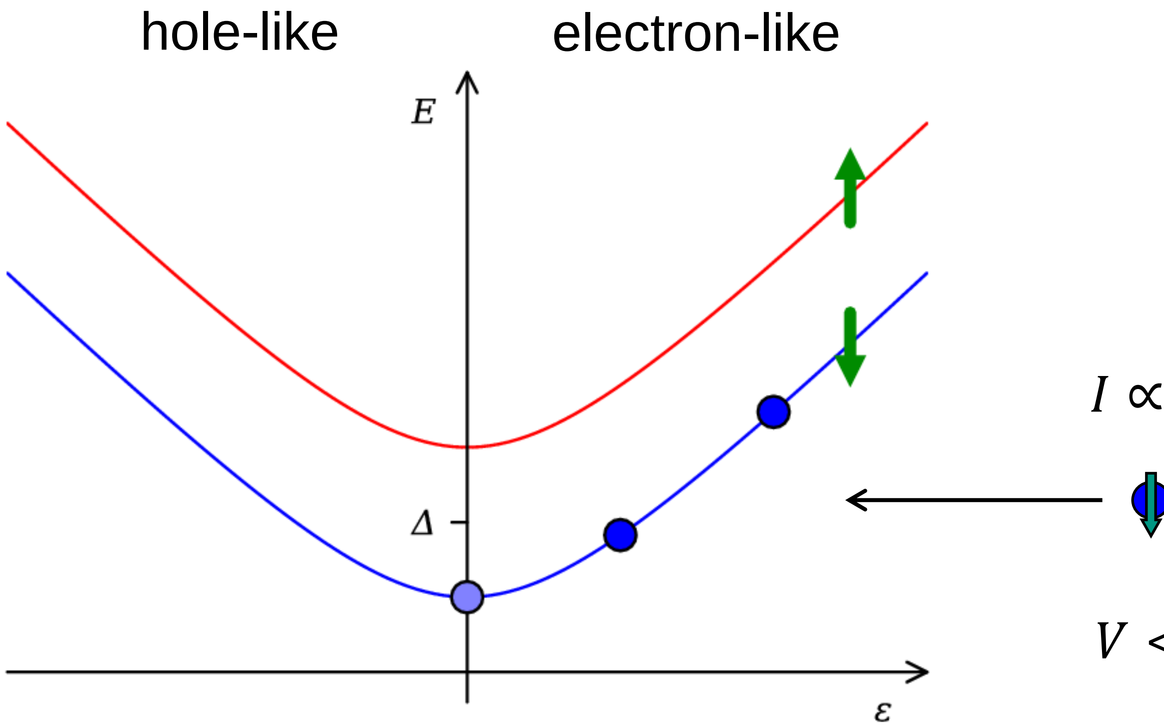
Experiment – *spin injection vs signal*



nonlocal conductance follows spin injection

Model – *injection*





$I \propto G_\downarrow$

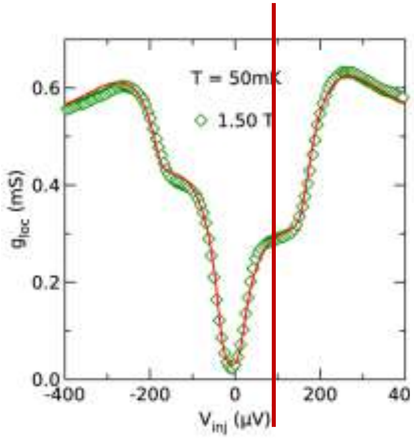
$V < 0$

charge imbalance $Q^*_\downarrow < 0$

spin accumulation $S_\downarrow > 0$

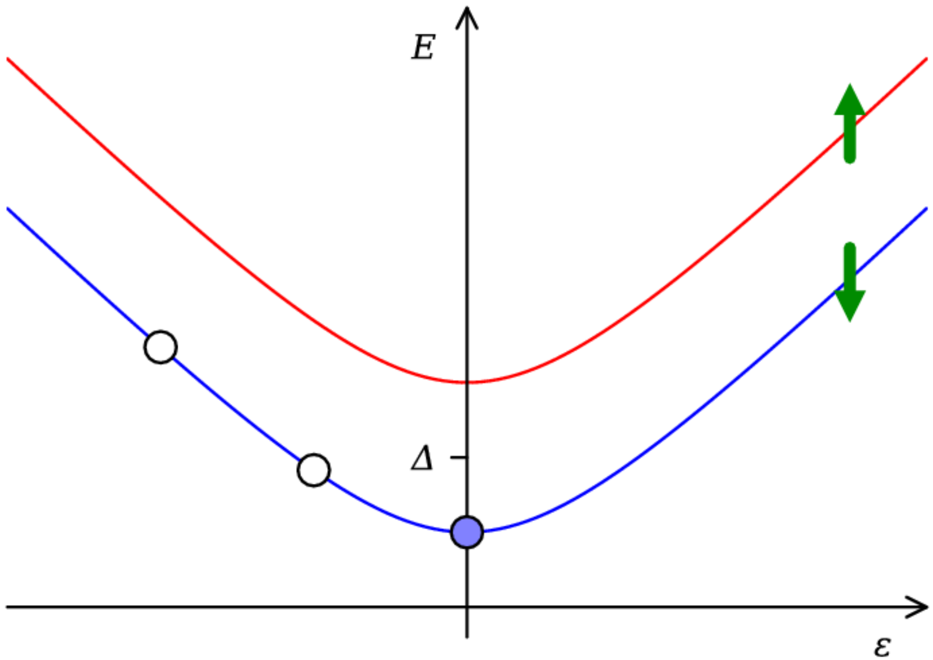
inject spin-down electrons

Model – *injection*

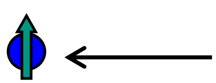


hole-like

electron-like



$I \propto G_{\uparrow}$



$V > 0$

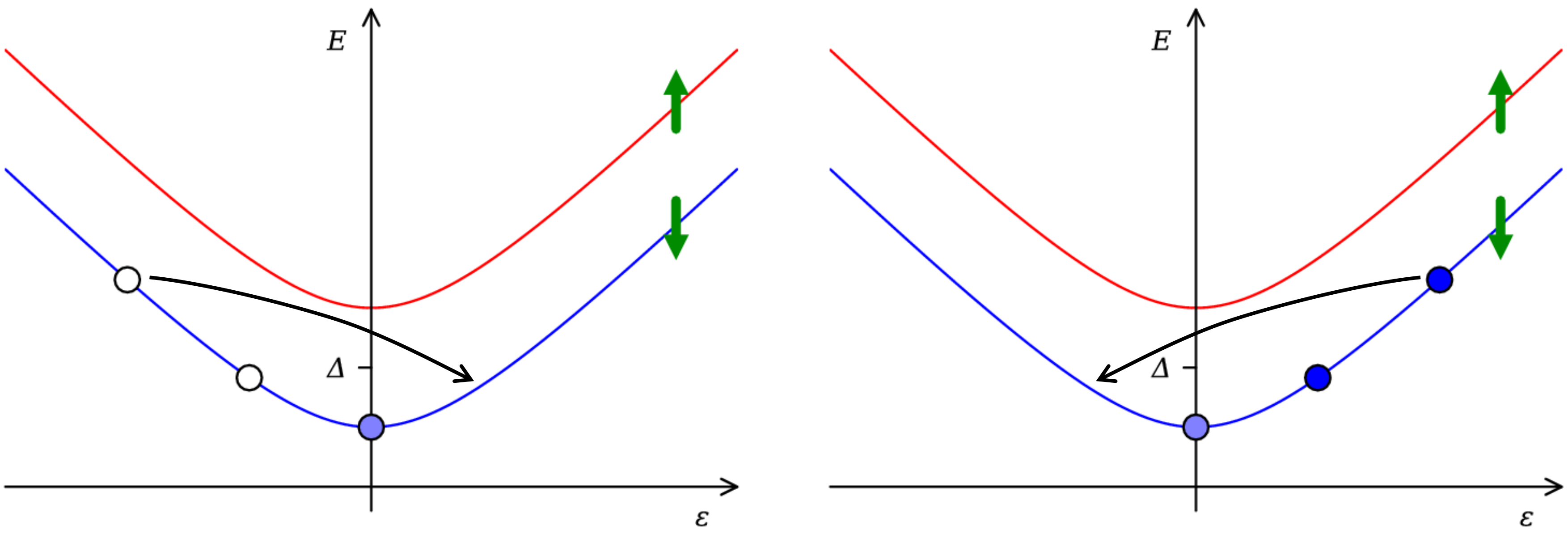
$Q^*_{\downarrow} > 0$

extract spin-up electrons

$S_{\downarrow} > 0$

Model – *charge relaxation*

charge relaxation for $d > \lambda_{Q^*}$



$V > 0$ $V < 0$

fast for $E \gtrsim \Delta$

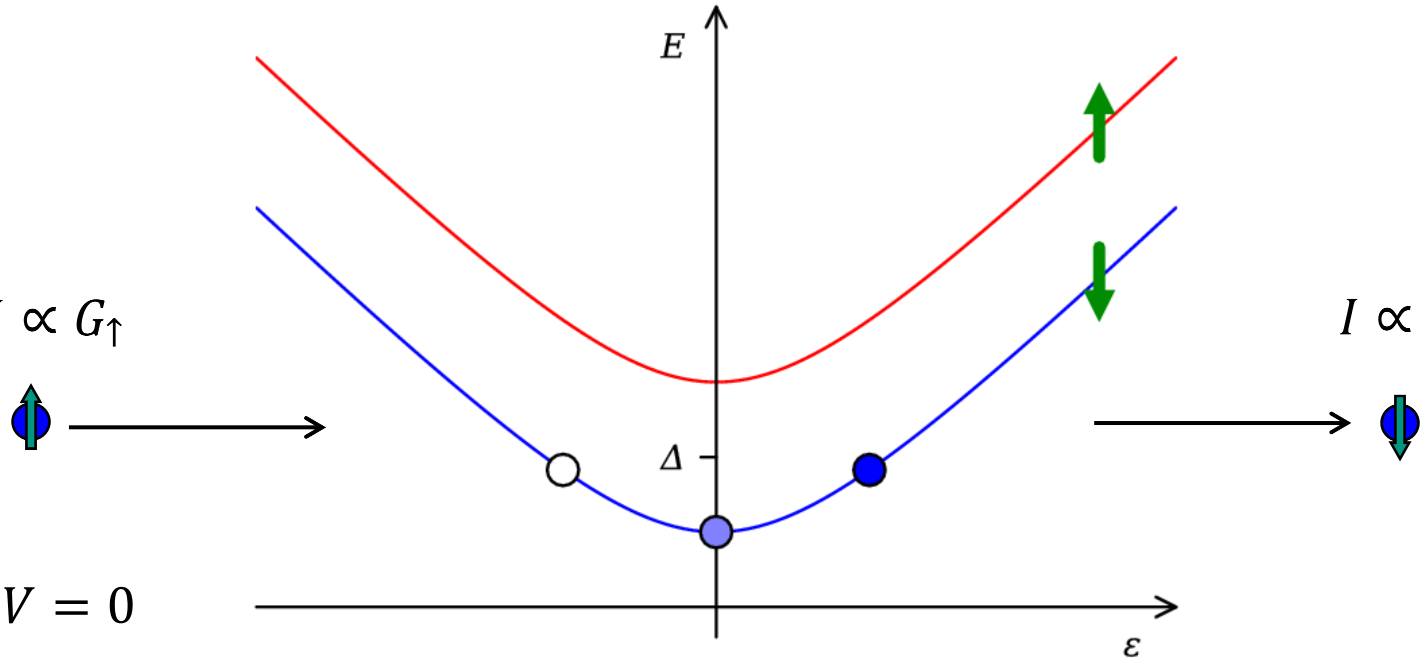
Model – *detector current*

$$I_{\mathrm{det}} = (G_\downarrow + G_\uparrow)(Q_\downarrow^* + Q_\uparrow^*) - (G_\downarrow - G_\uparrow)(S_\downarrow - S_\uparrow) \approx -(G_\downarrow - G_\uparrow)S_\downarrow$$

$I \propto G_\uparrow$

$I \propto G_\downarrow$

$V = 0$



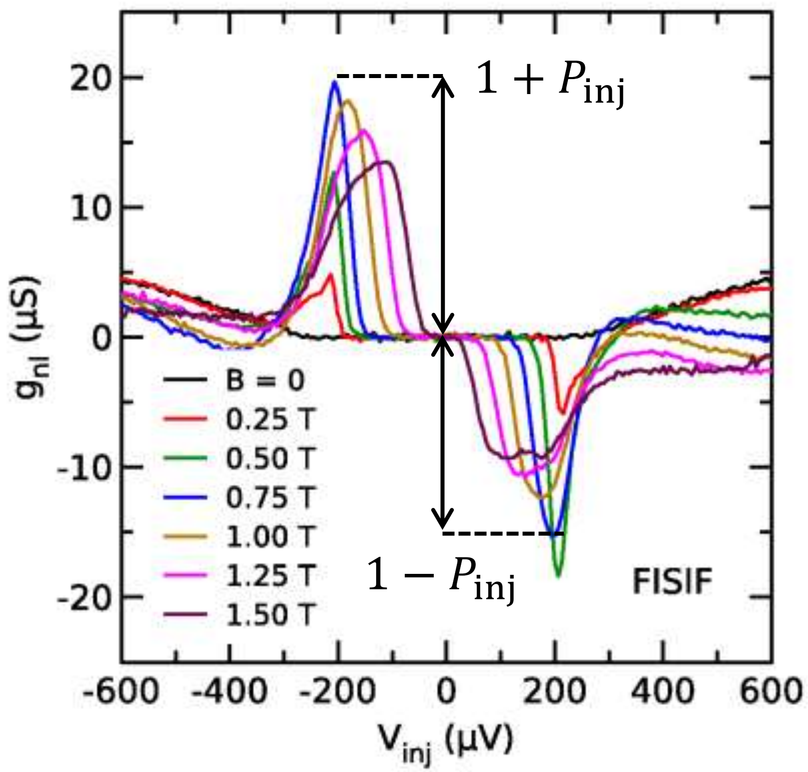
$Q_\downarrow^* \approx 0$

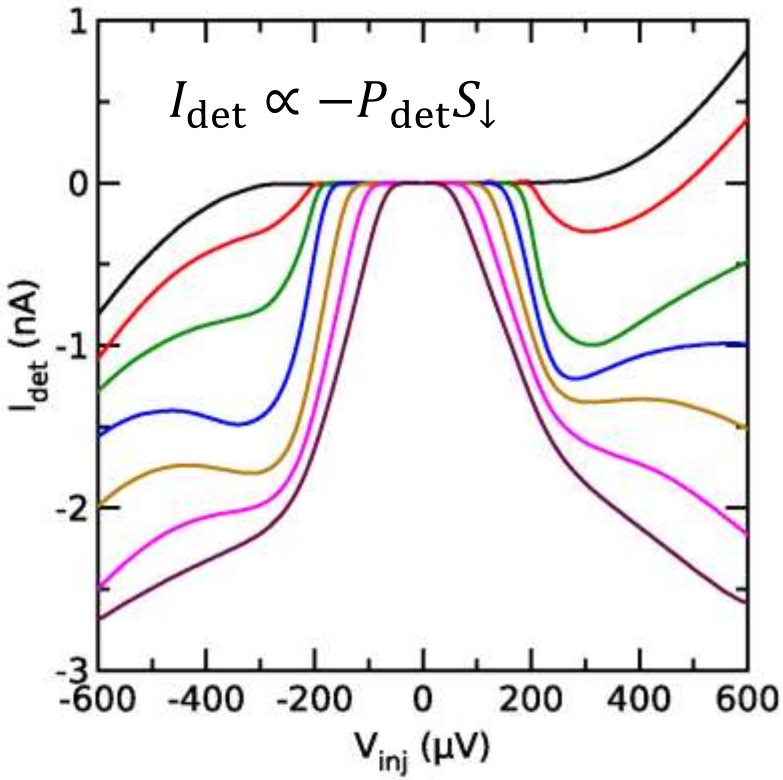
$S_\downarrow > 0$

spin charge separation

see Zhao & Hershfield, PRB **52**, 3632 (1995)

Interpretation – *detector current*

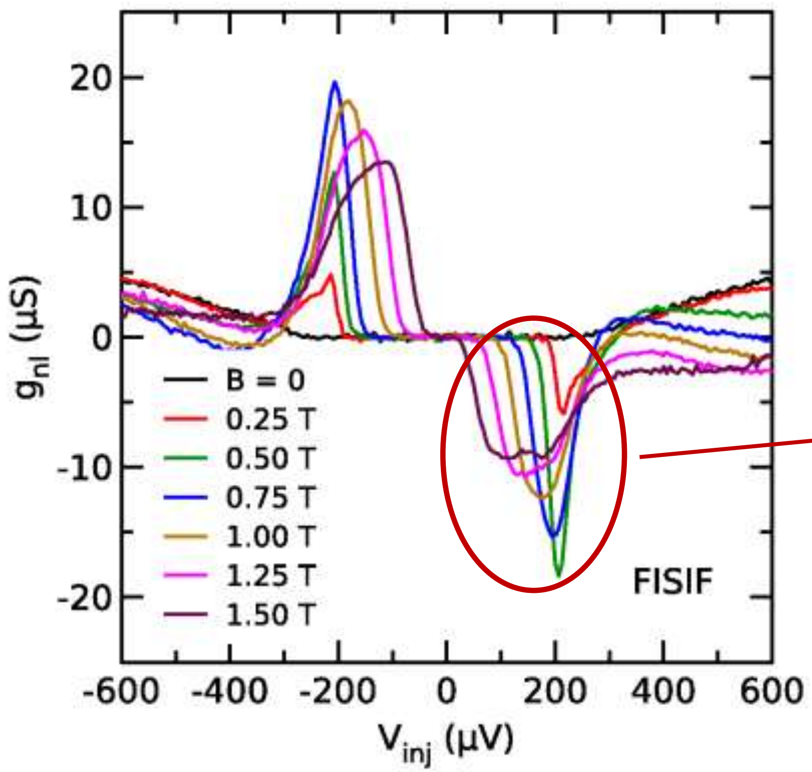


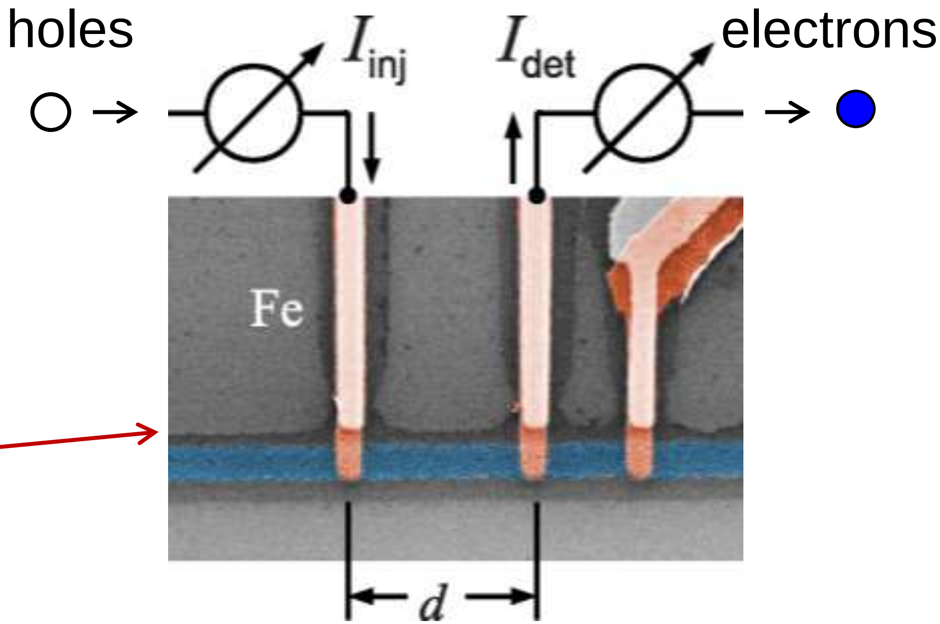


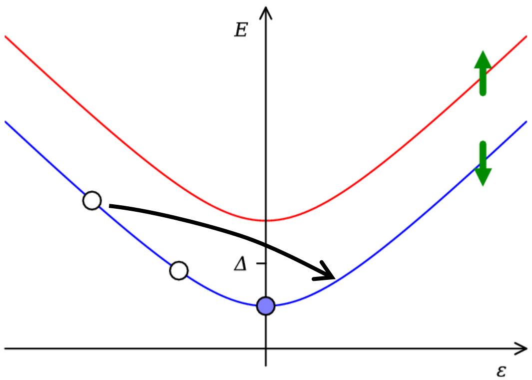
injector polarisation P_{inj}
→ different peak heights

detector polarisation P_{det}
→ sign of nonlocal current

Interpretation – *negative nonlocal signal*

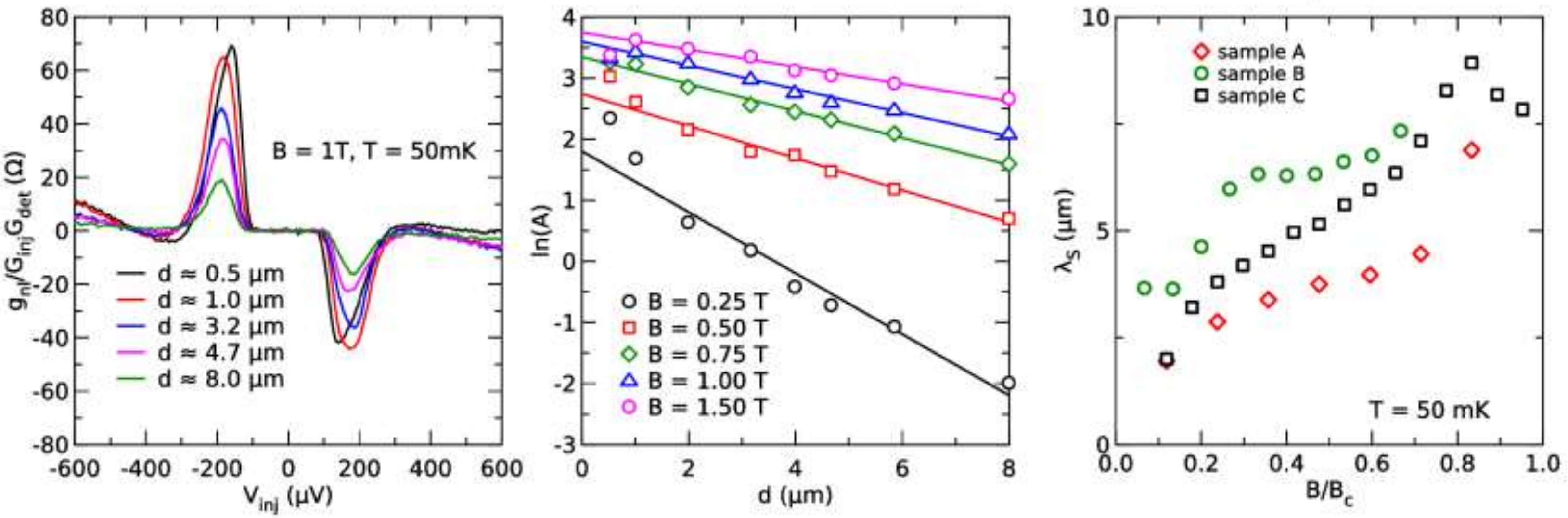




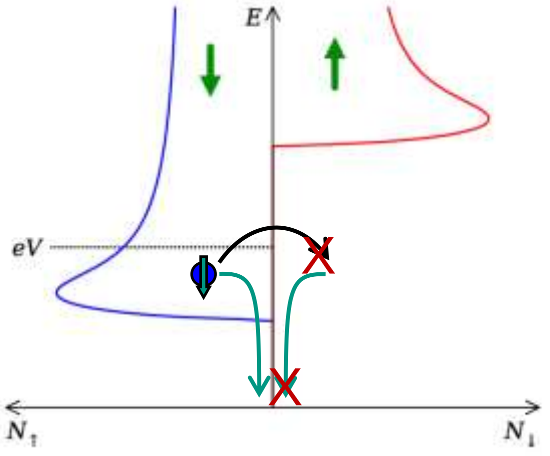


at positive bias: inject holes, get electrons.
looks like crossed Andreev reflection. why?
charge relaxation (no coherence needed)

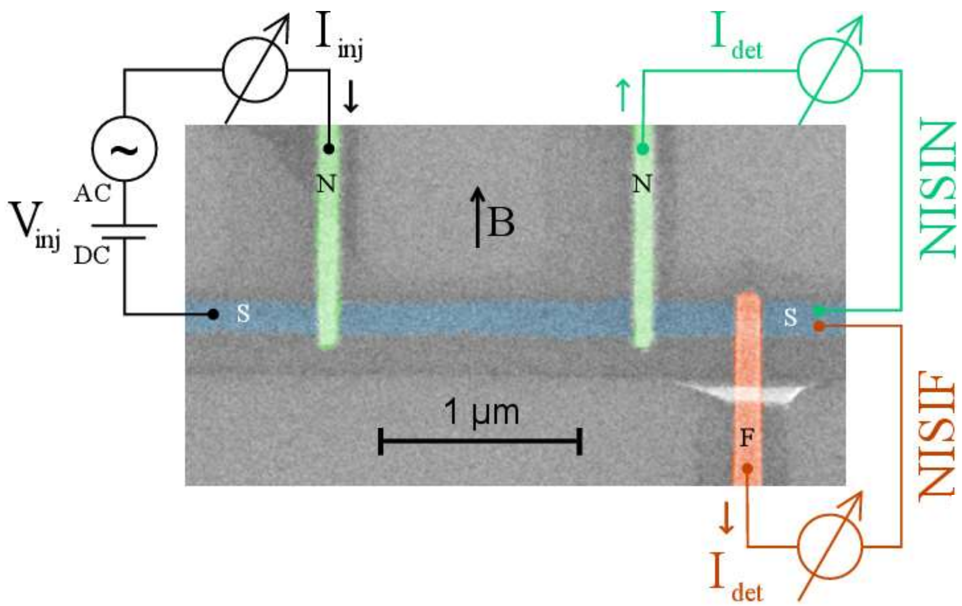
Experiment – *distance dependence*



- peak area decreases with contact distance
- signal persists up to 8 µm
- relaxation length $\lambda_S = 5 - 10\ \mu m$
  (compare to $\lambda_N = 370$ nm)
- what is the relaxation mechanism?



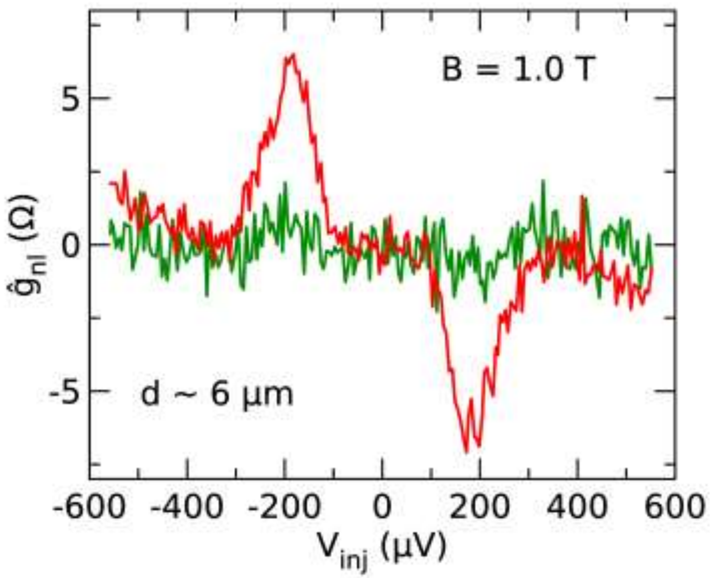
Experiment – *separating spin and charge*



contact distance 6 µm

no more charge at all

but: still spin



- direct comparison of charge and spin signal in same sample
- spin injection from normal metal

Wolf et al., Phys. Rev. B **87**, 024517 (2013)

Conclusions & Outlook

Conclusions

- Long range spin transport in Zeeman-split superconductors
- model for relaxation needed

Outlook

- thermoelectric effects
- manipulate and utilize spin currents

Thank you for your attention!

Hübler et al., Phys. Rev. B **81**, 184524 (2010)
Hübler et al., Phys. Rev. Lett. **109**, 207001 (2012)
Wolf et al., Phys. Rev. B **87**, 024517 (2013)

http://www.int.kit.edu/english/606.php